

WHAT IS CLAIMED IS:

1. A master oscillator power amplifier comprising:
a mode-locked fiber oscillator comprising a pair of reflective optical elements that form an optical resonator, at least one of said reflective optical elements being partially transmissive and having a reflection coefficient that is less than about 60%, said mode-locked fiber oscillator outputting a plurality of optical pulses; and
a fiber amplifier optically connected to said mode-locked fiber oscillator through a bi-directional optical connection such that light from said mode-locked fiber oscillator can propagate to said fiber amplifier and light from said fiber amplifier can propagate to said mode-locked fiber oscillator.
2. The pulsed fiber laser of Claim 1, wherein said mode-locked fiber oscillator is optically connected to said fiber amplifier through an optical fiber.
3. The pulsed fiber laser of Claim 1, further comprising one or more polarization maintaining optical fiber components.
4. The pulsed fiber laser of Claim 1, further comprising dispersion control elements to reduce dispersion.
5. The pulsed fiber laser of Claim 4, wherein said partially transmissive reflector comprises a Bragg grating having dispersion that reduced aggregate dispersion in said mode-locked fiber oscillator.
6. The pulsed fiber laser of Claim 1, further comprising a pump source optically coupled to said mode-locked fiber oscillator and said fiber amplifier to pump said fiber oscillator and said fiber amplifier.
7. The pulsed fiber laser of Claim 1, further comprising a first pump source optically coupled to said mode-locked fiber oscillator and a second pump optically coupled to said fiber amplifier.
8. The pulsed fiber laser of Claim 1, wherein said mode-locked fiber oscillator comprises a passive mode-locking device.
9. The pulsed fiber laser of Claim 1, further comprising a pulse compressor optically coupled to receive optical pulses output from said fiber amplifier.
10. A method of producing laser pulses, said method comprising:

propagating optical energy back and forth through a gain fiber by reflecting light from a pair of reflective elements on opposite ends of said gain fiber, less than about 60% of said light in said gain fiber being reflected back into said gain fiber by one of said reflectors, said pair of reflective elements together forming a resonant cavity that supports a plurality of resonant optical modes;

substantially mode-locking said resonant optical modes to produce a train of pulses;

propagating said train of optical pulses from said laser cavity through said one of said reflectors to a fiber amplifier along a bi-directional optical path from said laser cavity to said fiber amplifier; and

amplifying said laser pulses in said fiber amplifier.

11. The pulsed fiber laser of Claim 10, further comprising maintaining the polarization of said train of pulses using one or more polarization maintaining components.

12. The method of Claim 10, further comprising compressing said laser pulses.

13. A fiber-based master oscillator power amplifier comprising:

a mode-locked fiber oscillator comprising a resonant cavity and a gain medium, said mode-locked fiber oscillator producing a plurality of optical pulses;

a fiber amplifier comprising a gain fiber; and

a bi-directional optical path between said mode-locked fiber oscillator and said fiber amplifier permitting light from said mode-locked fiber oscillator to propagate to said fiber amplifier and light from said fiber amplifier to propagate to said mode-locked fiber oscillator.

wherein said mode-locked fiber oscillator comprise a first segment of fiber and said fiber amplifier comprise a second segment of optical fiber and said first and second segments form a substantially continuous length of optical fiber.

14. The master oscillator power amplifier of Claim 13, wherein said first and second segments are spliced together.

15. The master oscillator power amplifier of Claim 13, wherein said resonant cavity comprises first and second reflective optical elements, spontaneous emission from said fiber amplifier propagating along said bi-directional optical path to said mode-locked fiber

oscillator and at least partially reflecting from said second reflective optical element back to said fiber amplifier.

16. The pulsed fiber laser of Claim 13, further comprising polarization maintaining components for maintaining polarization.

17. The pulsed fiber laser of Claim 13, wherein said gain fiber comprises polarization maintaining optical fiber.

18. The pulsed fiber laser of Claim 13, wherein said mode-locked fiber oscillator further comprises optical components having dispersion that reduce dispersion in said mode-locked fiber oscillator.

19. The master oscillator power amplifier of Claim 13, wherein said second reflective optical element comprises a Bragg grating.

20. A method of producing laser pulses, said method comprising:
substantially mode-locking longitudinal modes of a laser cavity to produce laser pulses;
propagating said laser pulses from said laser cavity to a fiber amplifier;
amplifying said laser pulses in said fiber amplifier;
receiving amplified spontaneous emission emitted from said fiber amplifier at said laser cavity, a first portion of said spontaneous emission entering said laser cavity; and
retro-reflecting a second portion of said amplified spontaneous emission from said laser cavity back to said fiber amplifier to cause said second portion to be directed away from said cavity toward said fiber amplifier.

21. The pulsed fiber laser of Claim 20, propagating said pulses through a polarization maintaining optical component.

22. The pulsed fiber laser of Claim 20, propagating said pulses through a polarization maintaining delivery fiber.

23. The pulsed fiber laser of Claim 20, offsetting positive dispersion with negative dispersion to reduce the width of said laser pulses.

24. The method of Claim 20, wherein said amplified stimulated emission is retro-reflected back toward said fiber amplifier by a partially transmissive reflective optical element that forms said laser cavity.

25. The method of Claim 24, wherein said amplified stimulated emission is retro-reflected back by a Bragg grating toward said fiber amplifier.

26. The method of Claim 20, further comprising compressing said laser pulses.

27. A fiber master oscillator power amplifier comprising:

a mode-locked fiber oscillator comprising a first portion of optical fiber and a pair of reflectors spaced apart to form a fiber optic resonator in said first fiber portion, at least one of said fiber reflectors comprising a partially transmissive fiber reflector, said mode-locked fiber oscillator outputting a plurality of optical pulses; and

a fiber amplifier comprising a second portion of optical fiber optically connected to said partially transmissive fiber reflector to receive said optical pulses from said mode-locked oscillator, said second portion of optical fiber having gain to amplify said optical pulses,

wherein said first portion of optical fiber, said partially transmissive fiber reflector, and said second portion of optical fiber comprise continuous path formed by optical fiber uninterrupted by non-fiber optical components.

28. The fiber master oscillator power amplifier of Claim 27, wherein said at least one of said fiber reflectors has a reflection coefficient that is less than about 60%.

29. The fiber master oscillator power amplifier of Claim 27, wherein said first portion of optical fiber in said mode-locked fiber oscillator is doped to provide gain.

30. A master oscillator power amplifier comprising:

a mode-locked fiber oscillator comprising a pair of reflective optical elements that form an optical resonator, at least one of said reflective optical elements comprising a partially transmissive Bragg fiber grating having a reflection coefficient that is less than about 60%, said mode-locked fiber oscillator outputting a plurality of optical pulses; and

a fiber amplifier optically connected to said oscillator through an optical connection to said partially transmissive Bragg fiber grating.

31. A master oscillator power amplifier comprising:

a mode-locked fiber oscillator comprising a pair of reflective optical elements that form an optical resonator, at least one of said reflective optical elements being partially transmissive and having a reflection coefficient that is less than about 60%, said mode-locked fiber oscillator outputting a plurality of optical pulses;

a fiber amplifier optically connected to said oscillator through an optical connection to said at least one partially transmissive reflective optical elements; and

a pump source optically connected to said mode-locked fiber oscillator and said fiber amplifier to pump said mode-locked fiber oscillator and said fiber amplifier.

32. A frequency comb source comprising:

a mode-locked fiber oscillator comprising a resonant Fabry-Perot optical cavity having a cavity length, L , said mode-locked fiber oscillator outputting optical pulses and corresponding frequency components separated by a frequency spacing, f_{rep} and offset from a reference frequency by a frequency offset, f_{ceo} ;

a non-linear optical element positioned to receive said optical pulses, said non-linear optical element having sufficient optical non-linearity to generate additional frequency components that together with said plurality of frequency components output by said mode-locked oscillator form a first set of frequencies separated by said frequency spacing, f_{rep} and offset from said reference frequency by said frequency offset, f_{ceo} ;

an interferometer optically coupled to receive said first set of frequencies, said interferometer comprising a frequency shifter that receives said first set of frequencies and that superimposes a second set of frequencies on said first set of frequencies received by said frequency shifter, said second set of frequencies interfering with said first set of frequencies to produce beat frequencies; and

an optical detector optically receiving said beat frequencies, said optical detector having an output for outputting said beat frequencies.

33. The frequency comb source of Claim 32, further comprising a feedback system having an input for receiving said beat frequencies, said feedback system in

communication with said mode-locked fiber oscillator so as to control the offset frequency, f_{ceo} based on said beat frequencies.

34. The frequency comb source of Claim 33, wherein said feedback system has an input for a reference signal and phase detection electronics to compare at least one of said beat frequencies with the reference signal.

35. The frequency comb source of Claim 32, wherein said reference frequency comprises zero frequency.

36. The frequency comb source of Claim 32, wherein said non-linear optical element comprises a non-linear optical fiber.

37. The frequency comb source of Claim 32, wherein said frequency shifter comprises a frequency multiplier.

38. The frequency comb source of Claim 37, wherein said frequency multiplier comprises a crystal frequency doubler.

39. The frequency comb source of Claim 37, wherein said frequency multiplier comprises a crystal difference frequency mixer.

40. The frequency comb source of Claim 32, wherein said first and second sets of frequencies are interfered over substantially the same optical path in said interferometer.

41. The frequency comb source of Claim 32, wherein said interferometer comprises a group delay compensator that compensates for a difference in optical path between said first and second sets of frequencies interfering in said interferometer, said group delay compensator reducing said optical path difference to substantially zero.

42. The frequency comb source of Claim 32, wherein said interferometer comprises an optical path having first and second portions with opposite first and second dispersion values, said first dispersion value providing relatively lower group velocity for a first train of optical pulses corresponding to said first set of frequencies and said second dispersion value providing relatively higher group velocity for a second pulse train corresponding to said second set of frequencies such that said first and second pulse trains substantially overlap in time and thereby interfere.

43. The frequency comb source of Claim 32, wherein the interferometer comprises a group delay compensator element operated in transmission or reflection.

44. The frequency comb source of Claim 43, wherein said group delay compensator element is selected from the group consisting of a segment of dispersive optical fiber and a planar waveguide element having a group delay dispersion different for the first and second sets of frequencies.

45. The frequency comb source of Claim 32, wherein said non-linear optical element has positive dispersion to lower the noise related to Raman processes in said non-linear optical element.

46. The frequency comb source of Claim 45, wherein said non-linear optical element comprises a segment of non-linear fiber comprising non-linear bismuth-oxide optical glass.

47. A method of producing a frequency comb, said method comprising:

substantially mode-locking longitudinal modes of a fiber laser cavity so as to produce laser pulses;

propagating said laser pulses through a non-linear optical element so as to produce a first plurality of frequency components offset from a reference frequency by frequency offset, f_{ceo} ;

propagating said laser pulses along an optical path that leads to an optical detector;

generating a second plurality of frequency components from said first plurality of frequency components and propagating said first and second plurality of frequency components on said optical path leading to said optical detector;

interfering said first plurality of optical components with said second set of optical components along said optical path to said optical detector so as to produce at least one beat frequency; and

using said at least one beat frequency to stabilize said offset frequency, f_{ceo} .

48. The method of Claim 47 further comprising varying the dispersion along a portion of said optical path such that a first set of pulses corresponding to said first plurality of frequencies propagates at a first group velocity and a second set of pulses corresponding to said second set of frequencies propagates at a second group velocity so that said first set of pulses substantially overlaps said second set of pulses in time at said detector.

49. The method of Claim 47, wherein said non-linear optical element has positive dispersion to reduce noise related to Raman processes.

50. A frequency comb source comprising:

a mode-locked fiber oscillator comprising an optical fiber and a pair of reflective optical elements that form an optical cavity that supports a plurality of optical modes, said mode-locked fiber oscillator mode-locking said optical modes to produce optical pulses and frequency components having a frequency spacing, f_{rep} , and offset from a reference frequency by a frequency offset, f_{ceo} ;

a substantially non-linear optical element disposed to receive said optical pulses, said substantially non-linear optical element having sufficient optical non-linearity to generate additional frequency components that together with said frequency components output from said mode-locked fiber oscillator form a first plurality of frequency components spaced by said frequency spacing, f_{rep} , and offset from said reference frequency by said frequency offset, f_{ceo} ;

an interferometer that interferes a second plurality of optical frequency components with said first plurality of frequency components thereby producing beat frequencies; and

an optical detector optically connected to said interferometer to detect said beat frequencies, said optical detector having an output that outputs said beat frequencies.

51. The frequency comb of Claim 50, further comprising a first feedback system and a second feedback system each having an input for receiving said beat frequencies, said first and second feedback systems each comprising a phase lock loop to compare said beat frequencies with one or more reference frequencies, said first electronic feedback system connected to said mode-locked fiber oscillator to control said offset frequency, f_{ceo} , based on said beat frequencies, said second feedback system connected to said mode-locked fiber oscillator to control said repetition frequency, f_{rep} .

52. The frequency comb source of Claim 51, further comprising a transducer that perturbs said optical fiber in said mode-locked fiber oscillator in response to feedback from said first feedback system to alter the offset frequency, f_{ceo}

53. The frequency comb source of Claim 52, where said transducer comprises one or more heating elements.

54. The frequency comb source of Claim 52, wherein said transducer comprises an electro-mechanical transducer.

55. The frequency comb source of Claim 51, further comprising a transducer that perturbs said optical fiber in said mode-locked fiber oscillator in response to feedback from said second feedback system to alter the repetition frequency, f_{rep} .

56. The frequency comb source of Claim 55, where said transducer comprises one or more heating elements.

57. The frequency comb source of Claim 55, wherein said transducer comprises an electro-mechanical transducer.

58. The frequency comb source of Claim 51, further comprising an optical pump for pumping said mode-locked fiber oscillator, said optical pump selectively adjusting said pumping in response to feedback from said feedback system to control the offset frequency, f_{ceo} .

59. The frequency comb source of Claim 51, further comprising a transducer that adjusts one of said reflective optical elements in response to feedback from said first feedback system to alter the offset frequency, f_{ceo} .

60. The frequency comb source of Claim 59, wherein said transducer comprises an electro-mechanical transducer that selectively alters the position of the reflective optical element.

61. The frequency comb source of Claim 59, wherein said reflective optical element comprises a chirped Bragg grating and said transducer comprises an electro-mechanical transducer for adjusting said chirped Bragg grating.

62. The frequency comb source of Claim 59, wherein said reflective optical element comprises a chirped Bragg grating and said transducer comprises a variable temperature element for altering the temperature of the chirped Bragg grating.

63. The frequency comb source of Claim 51, further comprising an optical coupler for coupling output from said oscillator to measure said f_{rep} , said second feedback system adjusting said oscillator based on said measured f_{rep} .

64. The frequency comb source of Claim 51, further comprising an amplifier disposed to receive said optical pulses and an optical coupler for coupling output from said amplifier to measure said f_{rep} , said second feedback system adjusting said oscillator based on said measured f_{rep} .

65. The frequency comb source of Claim 50, wherein said interferometer comprises a single arm interferometer.

66. A frequency comb source comprising:

a mode-locked fiber oscillator having a resonant cavity comprising an optical fiber having a length, L , said resonant cavity supporting a plurality of optical modes, said mode-locked fiber oscillator mode-locking said plurality of optical modes to produce a mode-locked optical signal comprising frequency components separated by a frequency spacing, f_{rep} and offset from a reference frequency by a frequency offset, f_{ceo} ; and

a substantially non-linear optical element positioned to receive said mode-locked optical signal, said substantially non-linear optical element having sufficient optical non-linearity to generate additional frequency components that together with said plurality of frequency components output by said mode-locked oscillator form a first set of frequencies separated by said frequency spacing, f_{rep} and offset from said reference frequency by said frequency offset, f_{ceo} .

67. The frequency comb source of Claim 66, wherein said mode-locked fiber oscillator comprises first and second dispersive optical elements selected to have positive and negative dispersion, respectively, said first and second dispersive optical elements further being selected to provide a total dispersion in said mode-locked fiber oscillator less than about $10,000 \text{ femtosec}^2 \times L$, thereby reducing noise in said f_{ceo} .

68. The frequency comb source of Claim 67, wherein one of said first and second dispersive optical elements comprises an optical fiber segment and one of said first and second dispersive optical element comprises a chirped fiber Bragg grating.

69. The frequency comb source of Claim 67, wherein said first dispersive optical element comprises an optical fiber segment with positive dispersion and said second

dispersion optical element comprises an optical fiber segment selected with negative dispersion.

70. The frequency comb source of Claim 67, wherein one of said first and second dispersive optical elements comprise a waveguide and one of said first and second dispersive optical elements comprises a bulk optics element.

71. The frequency comb source of Claim 70, wherein said waveguide comprises an optical fiber segment.

72. The frequency comb source of Claim 66, further comprising a fiber amplifier comprising an optical fiber doped to provide gain, said amplifier amplifying output from said oscillator.

73. The frequency comb source of Claim 72, wherein said amplifier is substantially nonlinear.

74. The frequency comb source of Claim 73, wherein said nonlinear amplifier provides spectral broadening.

75. The frequency comb source of Claim 73, wherein said amplifier has positive dispersion.

76. The frequency comb source of Claim 73, wherein said amplifier has negative dispersion.

77. The frequency comb source of Claim 73, wherein said amplifier has positive dispersion, said amplifier receiving a chirped input pulse with a positive chirp such that high optical frequency components lag behind the low optical frequency components.

78. The frequency comb source of Claim 73, wherein said amplifier has negative dispersion, said amplifier receiving a chirped input pulse with a positive chirp such that high optical frequency components lag behind the low optical frequency components.

79. The frequency comb source of Claim 66, further comprising a compressor comprising a dispersive fiber optically coupled to receive the mode-locked signal.

80. The frequency comb source of Claim 66, further comprising an amplifier that amplifies said mode-locked signal.

81. The frequency comb source of Claim 67, wherein said dispersion of said mode-locked fiber oscillator is less than or equal to about 20,000 femtosec².

82. The frequency comb source of Claim 67, wherein said dispersion of said mode-locked fiber oscillator is less than or equal to about 10,000 femtosec².

83. The frequency comb source of Claim 67, wherein said dispersion of said mode-locked fiber oscillator is less than or equal to about 5,000 femtosec².

84. A method of reducing frequency noise of a frequency comb produced by a fiber-based frequency comb source comprising a mode-locked fiber oscillator having an optical cavity comprising an optical fiber having a length, L, said method comprising reducing the dispersion in said mode-locked fiber oscillator to less than about 10,000 femtosec² × L.

85. The method of Claim 84, wherein said dispersion of said oscillator is reduced to less than or equal to about 20,000 femtosec².

86. The method of Claim 84, wherein said dispersion of said oscillator is reduced to less than or equal to about 10,000 femtosec².

87. The method of Claim 84, wherein said dispersion of said oscillator is reduced to less than or equal to about 5,000 femtosec².